# Report Documentation Page

*Form Approved*
*OMB No. 0704-0188*



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|---|---|---|
| 1. REPORT DATE<br>**2010** | 2. REPORT TYPE | 3. DATES COVERED<br>**00-00-2010 to 00-00-2010** |

| | |
|---|---|
| 4. TITLE AND SUBTITLE<br>**Large-Scale Arrays of Single Layer Graphene Resonators** | 5a. CONTRACT NUMBER |
| | 5b. GRANT NUMBER |
| | 5c. PROGRAM ELEMENT NUMBER |
| 6. AUTHOR(S) | 5d. PROJECT NUMBER |
| | 5e. TASK NUMBER |
| | 5f. WORK UNIT NUMBER |
| 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)<br>**Cornell University,Applied and Engineering Physics,Ithaca,NY,14853** | 8. PERFORMING ORGANIZATION REPORT NUMBER |
| 9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) | 10. SPONSOR/MONITOR’S ACRONYM(S) |
| | 11. SPONSOR/MONITOR’S REPORT NUMBER(S) |

12. DISTRIBUTION/AVAILABILITY STATEMENT
**Approved for public release; distribution unlimited**

13. SUPPLEMENTARY NOTES
**Report from The 2009-2010 Cornell NanoScale Science & Technology Facility Research Accomplishments.**

14. ABSTRACT

15. SUBJECT TERMS

| 16. SECURITY CLASSIFICATION OF: | | | 17. LIMITATION OF ABSTRACT | 18. NUMBER OF PAGES | 19a. NAME OF RESPONSIBLE PERSON |
|---|---|---|---|---|---|
| a. REPORT<br>**unclassified** | b. ABSTRACT<br>**unclassified** | c. THIS PAGE<br>**unclassified** | **Same as Report (SAR)** | **2** | |

**Standard Form 298 (Rev. 8-98)**
Prescribed by ANSI Std Z39-18

# Large-Scale Arrays of Single Layer Graphene Resonators

**CNF Project # 900-00**
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## Abstract:

**We use chemical vapor deposition-grown graphene to produce large arrays of suspended, single layer graphene membranes with lithographically defined shape, and aligned to microfabricated structures on a substrate. We measure the mechanical resonance frequency and tune it with both electrostatic gate voltage and temperature. Resonator quality factors improve with temperature, from 20-300 at 300 K to 9000 at 10 K. These measurements show that it is possible to produce large arrays of graphene resonators that maintain graphene's excellent electrical and mechanical properties.**

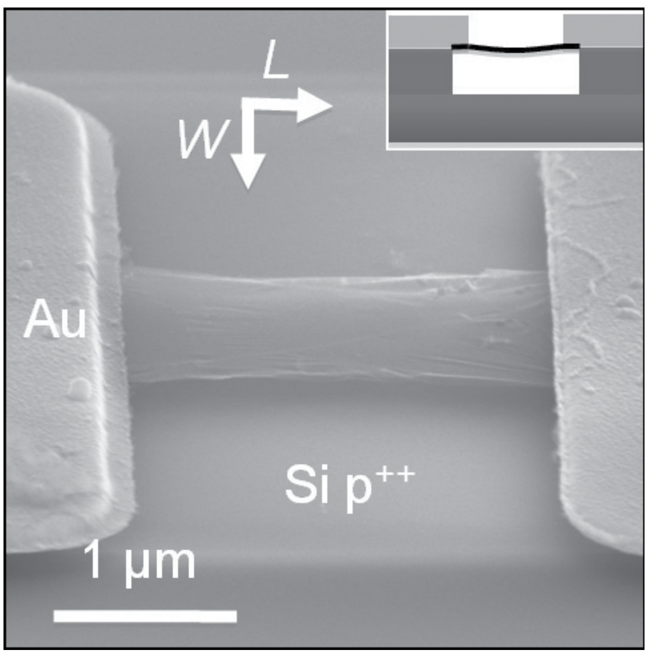


*Figure 1: Angled SEM image of a suspended graphene membrane clamped to gold electrodes. Inset is the cross-section.*

## Summary of Research:

Graphene, a single layer of carbon atoms bonded in a hexagonal lattice, is the prototypical two-dimensional membrane. Graphene's unparalleled strength, small mass per unit area, ultra-high aspect ratio, and unusual electronic properties make it an ideal candidate for nano-electro-mechanical systems (NEMS) [1,2]. Until recently, high quality graphene membranes could only be made in small batches using mechanical exfoliation [1] or on a silicon carbide substrate [3]. In this report, we demonstrate a new method to produce large arrays of suspended, single layer graphene membranes on an arbitrary substrate using graphene grown by chemical vapor deposition (CVD). We mechanically resonate the graphene membranes and control the frequency and quality factor by electrostatic tuning and temperature.

To fabricate the suspended membranes shown in Figure 1, we started by using CVD to grow graphene on copper foil squares 2 cm on a side [4], and verified by Raman microscopy the graphene to be single layer (> 90%) with low disorder. We transferred the patterned graphene onto a poly(methyl methacrylate) (PMMA) membrane by spinning PMMA onto the patterned graphene surface, etching the copper away using ferric chloride, and rinsing the remaining PMMA membrane in water until there was no remaining acid. We transferred the PMMA membrane from the water by hand onto the surface of a silicon wafer covered with 285 nm of oxide.

After letting the chip dry completely, we removed the PMMA by dissolving it in dichloromethane. We then patterned the deposited graphene into an array of rectangles using oxygen plasma. We patterned 2 nm/150 nm thick chrome/gold electrodes on top of the patterned graphene and used buffered hydrofluoric acid etch to completely remove the oxide under the graphene. Finally, we critical point dried the resonator. We estimate an 80% yield for membranes with $L < 3\ \mu m$ and $W < 5\ \mu m$. The main limitation to yield is tears in the graphene made during the transfer process.

We measured the graphene resonance using electronic mixing techniques. First, we measured electrical resistance versus back-gate voltage of the membrane and calculated a lower bound on mobility of the graphene $\mu \sim 4000\ cm^2/V{\bullet}s$, which is similar to the previously measured mobilities of CVD graphene on a substrate [4].

We measured the graphene resonance frequency as a function of electrostatic gate and temperature. We actuated the resonators electrostatically, and measured the motion using amplitude modulation (AM) [2] or frequency modulation (FM) mixing and extracted the resonance frequency and quality factor.

The graphene resonance frequency is highly tunable with gate voltage. Figure 2a shows the FM mixing current as a function of the drive frequency and electrostatic gate voltage at room temperature. The resonance frequency increases by more than a factor of 2 for large gate voltages relative to the frequency at zero gate voltage and is symmetric around a minimum close to zero gate voltage. Figures 2b-2c show the tuning of the same resonance at $T$ = 200 K, 150 K. As the temperature is decreased the frequency of the resonator at zero gate voltage rises, while the dependence of the resonance frequency on gate voltage becomes weaker, and even reverses in sign at 100 K.

Figure 3 shows the inverse quality factor of a resonator versus temperature for a fixed $V_{bg}$ = 3 V. The inset shows the frequency versus temperature over the same temperature range. As the temperature is decreased, the quality factor rises dramatically from 150 at room temperature to up to 9000 at 9 K. The inverse quality factor scales as $T^{\alpha}$, where $\alpha = 0.35 \pm 0.05$ from 9 K up to 40 K, and as $T^{\beta}$, where $\beta = 2.3 \pm 0.1$ from 40 K to room temperature. The temperature scaling and magnitude of the dissipation is very similar to what is found for both exfoliated graphene resonators [2] and carbon nanotube resonators, suggesting that a common dissipation mechanism is shared between the three systems. While there are many theories examining dissipation in graphene and nanotube resonators the dominant dissipation mechanism is still not understood.

The techniques described here provide a step toward practical graphene-based devices. This work shows that it is possible to fabricate large arrays of low mass, high aspect ratio, CVD-grown single-layer graphene membranes while maintaining the excellent electronic and mechanical properties that make graphene such a desirable material. These membranes produce low-mass, high-frequency, and highly-tunable nanomechanical resonators that are useful for applications in sensing and signal processing.

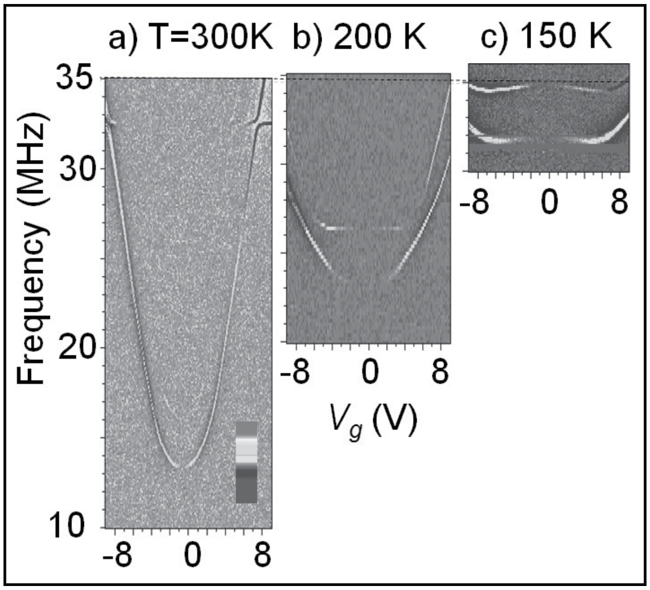


*Figure 2: a) FM mixing signal (colorscale = -100 pA to 100 pA) versus gate voltage and drive frequency at room temperature. The graphene resonance is getting tuned by the electrostatic gate voltage. b-d) evolution of the tuning for the same resonator at T = 200 K, 150 K, and 100 K respectively.*

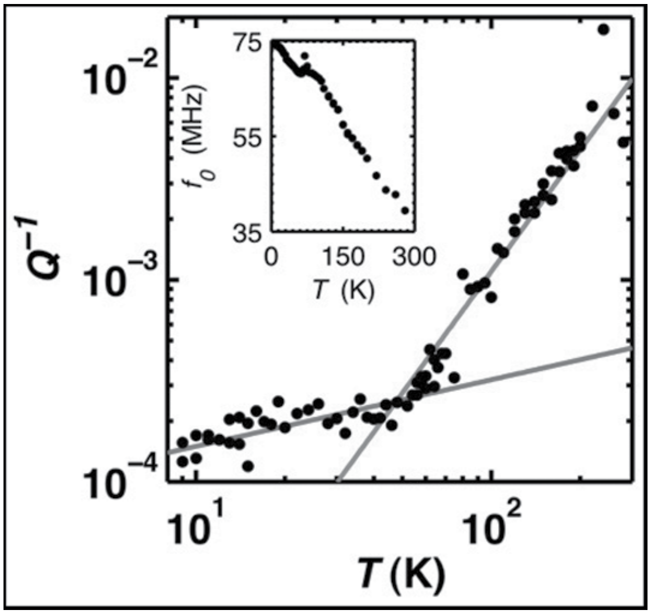


*Figure 3: Inverse quality factor versus temperature at $V_g$ = 3V; shallow and steep lines scale as T0.33 and T2 respectively.*

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[1] Bunch, J., et al., "Electromechanical Resonators from Graphene Sheets"; Science. 315, 5811, p. 490-493 (2007).

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[4] Li, X., et al., "Large-Area Synthesis of High-Quality and Uniform Graphene Films on Copper Foils"; Science, 324, 5932, p. 1312-1314 (2009).